



Compatibility of the Radio Frequency Mass Gauge with Composite Tanks

Greg Zimmerli, NASA Glenn Research Center, Cleveland, OH

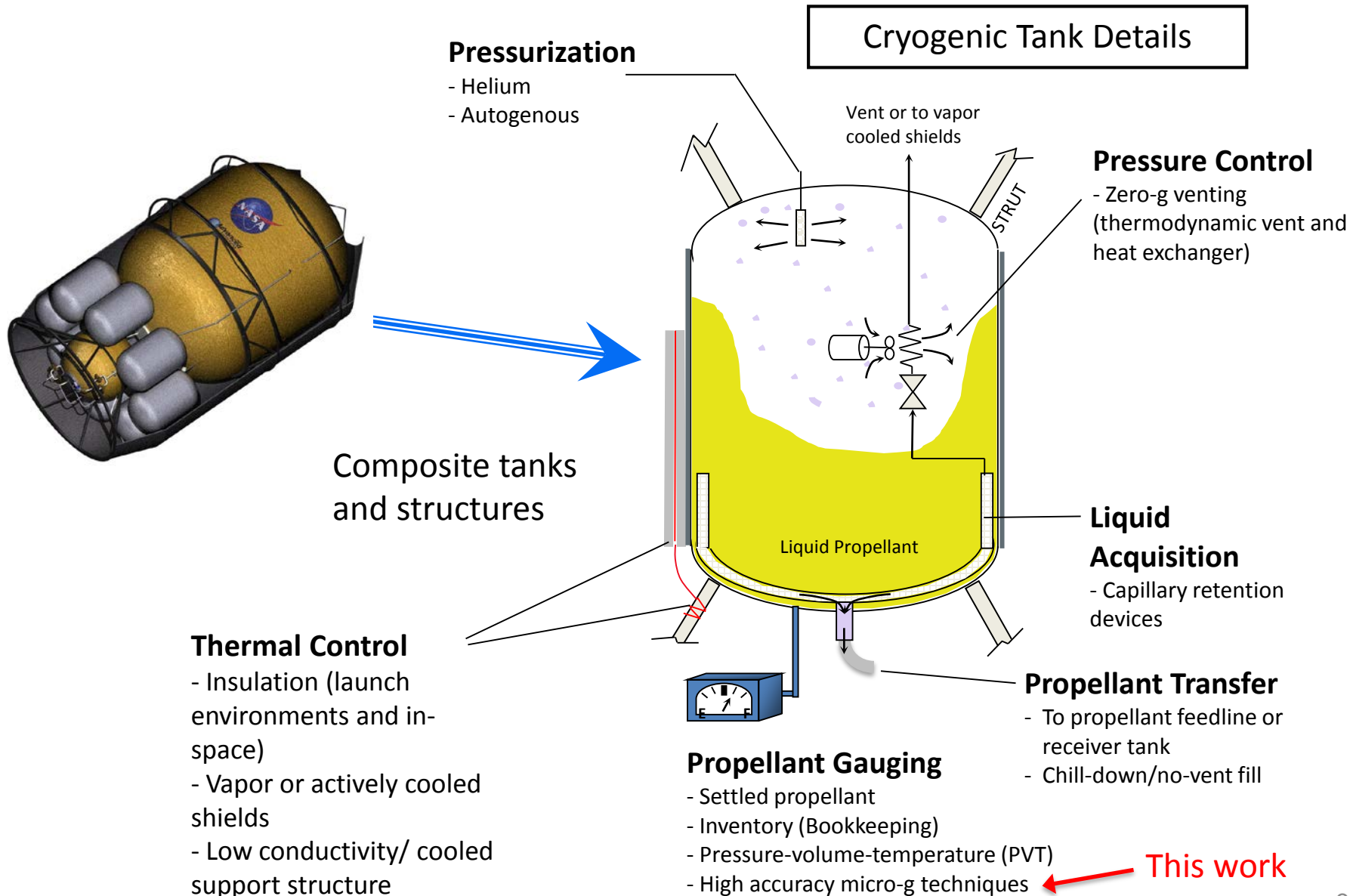
Carl Mueller, Vencore Inc., Cleveland, OH

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- Cryogenic Fluid Management Technologies for Space Applications
 - Motivation for this work
- Low-g propellant quantity gauging
 - Radio Frequency Mass Gauge (RFMG)
 - Principle of operation
 - RFMG operational requirements
- Graphite/Epoxy composite electrical tests
 - RF impedance analyzer
 - Waveguide reflectivity
 - Composite box; EMI testing
- RF modal testing in the Boeing 2.4m composite tank
- Summary & Conclusions

Space Cryo Fluid Management Technologies



Low-gravity propellant quantity gauging



Low-g propellant gauging: State of the art

- SOA for cryo's is settling and bookkeeping
- SOA for storables is thermal method, PVT, and bookkeeping

Several low-gravity cryo-propellant gauges have been developed and tested

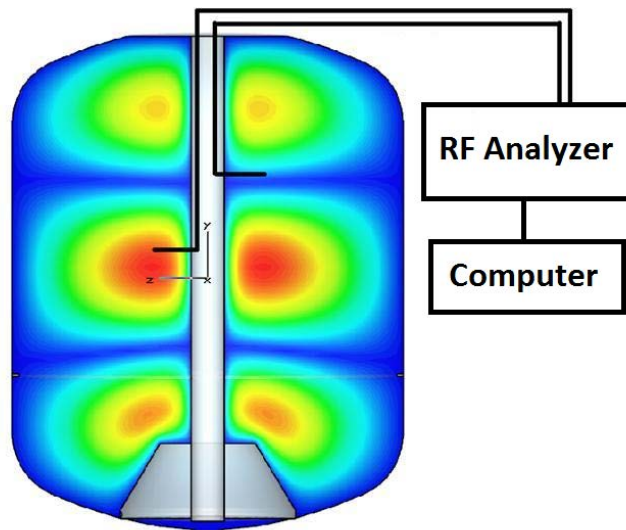
- Compression Mass Gauge (SwRI)
- Optical Mass Gauge (ATG, Inc.)
- Pressure-Volume-Temperature (NASA)
- Radio Frequency Mass Gauge (NASA)

The focus of this talk is on the Radio Frequency Mass Gauge, and its compatibility with composite tanks

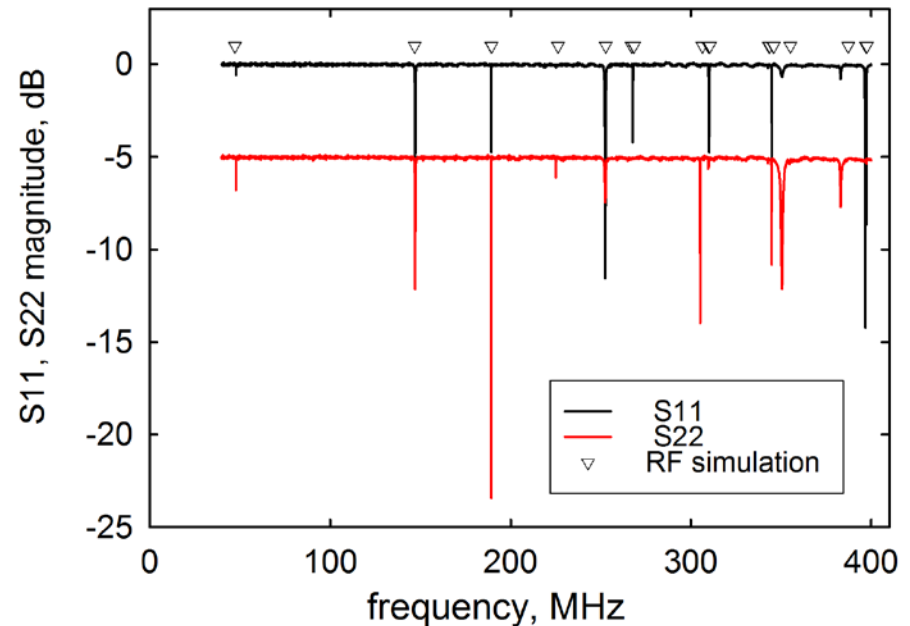
Radio Frequency Mass Gauge (RFMG)



Principle of operation:



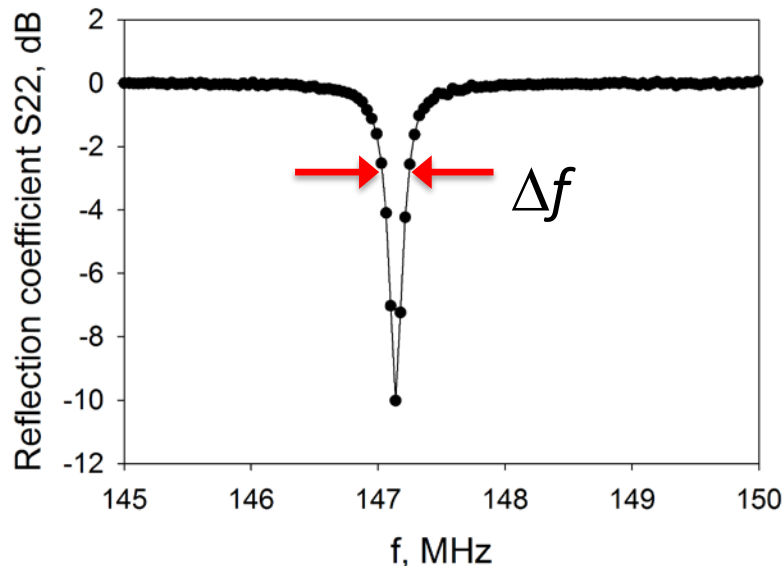
RF mode spectrum from 54" Al spherical tank



- RF simulation software can be used to predict tank RF modes
- The effect of a dielectric fluid can also be modeled ($c \rightarrow c/n$)
- The RFMG compares the measured RF mode frequencies with a database of simulations and finds a best match at some fill level
- RFMG has been tested with liquid hydrogen, oxygen, methane
 - Low-g aircraft testing with a simulant fluid, FC-77

For successful operation, the RFMG requires:

- Accurate model of the tank geometry and internal hardware
- Conductive tank walls to produce good quality tank modes**
- Good coupling between an antenna (or two) and the tank
 - The antenna acts as the source and receiver of the RF signal
- RF signal analyzer
- RF simulations
- Computer/algorithm for analyzing RF data



**Mode quality factor

$$Q = f/\Delta f$$

Want $Q \sim 100$ or better for
an accurate mode
frequency measurement

Mode quality factor

$$Q_{measured} = f/\Delta f$$

$$Q_{theory} \cong \frac{\mu}{\mu_c} \left(\frac{V}{S\delta} \right) \times (\text{geometrical factor of order 1})$$

Where μ/μ_c is the relative permeability, S = surface area, V = tank volume

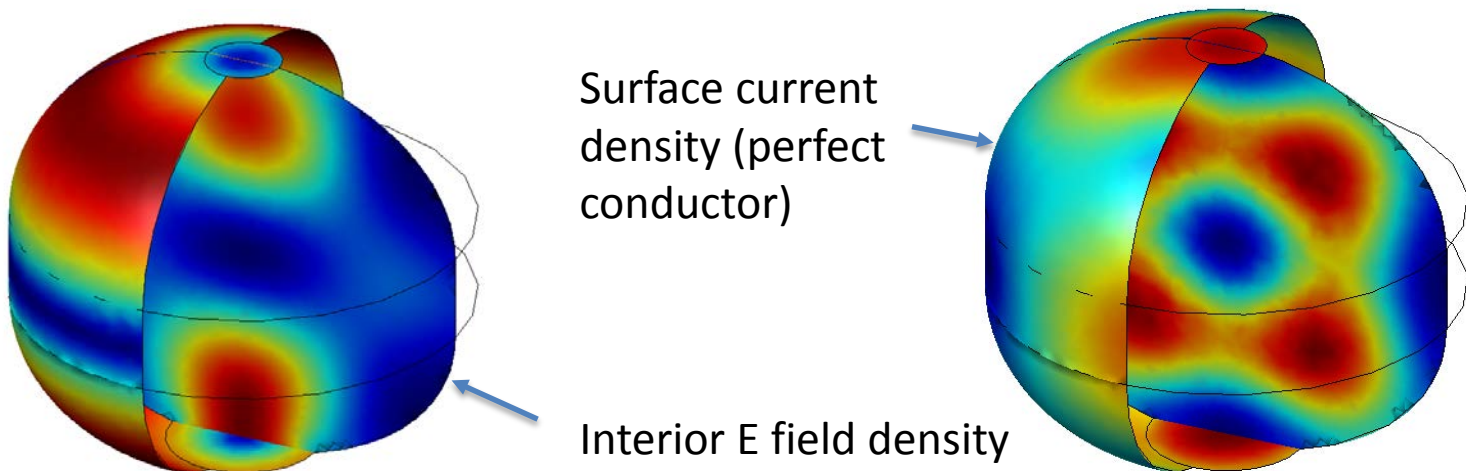
And $\delta = \sqrt{\frac{2}{\mu_c \omega \sigma}}$ is the penetration depth of the EM field

- High conductivity walls (metal) lead to high Q values
- What about a tank made from graphite/epoxy composite material?

Graphite/epoxy composite



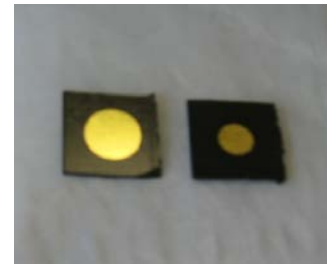
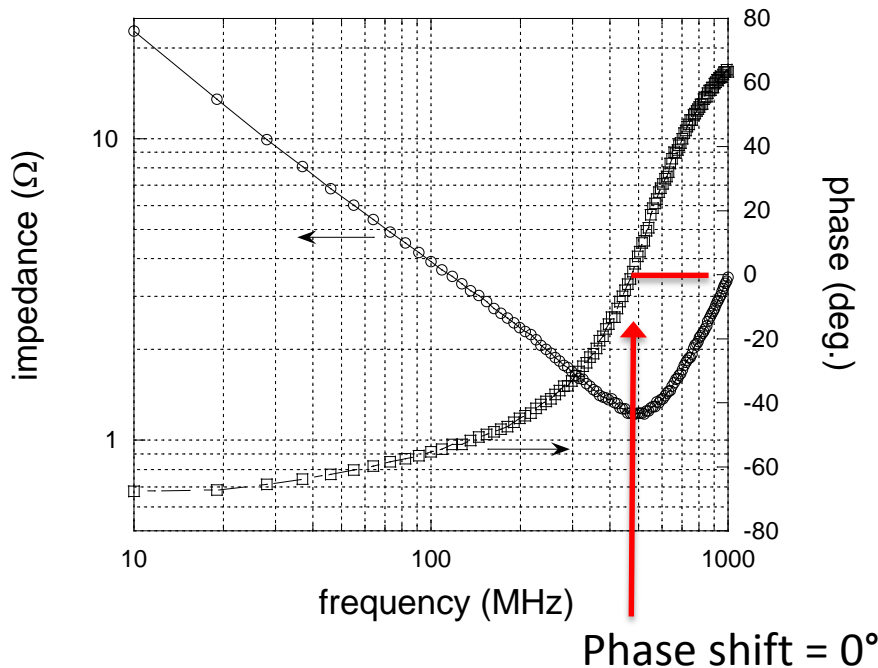
- Graphite/epoxy composite has anisotropic conductivity
 - In plane resistivity as low as 2.5×10^{-3} ohm-cm
 - Out of plane resistivity ranges from 10 – 1,000 ohm-cm
- Graphite fibers are conductors, but the effect of the fiber mesh on an RF tank spectrum was uncertain
- RF modes produce surface currents on inner tank walls, where the energy is dissipated
 - What is the effect of graphite/epoxy composite on tank Q-factor?



RF impedance analyzer measurements



- Acquired samples of 8552 IM7 graphite epoxy composite (16 ply, ~ 1 mm thick)
- Sputtered gold electrodes on each side
- Measured impedance normal to the sample thickness using an Agilent 16453A impedance analyzer from 10 – 1000 MHz
- Calibrated using alumina standard



$$\rho = \frac{RA}{L} = \frac{(1.2\Omega)(0.38 \text{ cm}^2)}{0.096 \text{ cm}} = 4.8 \Omega - \text{cm}$$

Calculated Q factor for a 2m tank:

$$Q_{\text{calc}} = 67$$

Expect higher value since this measurement is normal to the sample thickness

Waveguide measurements



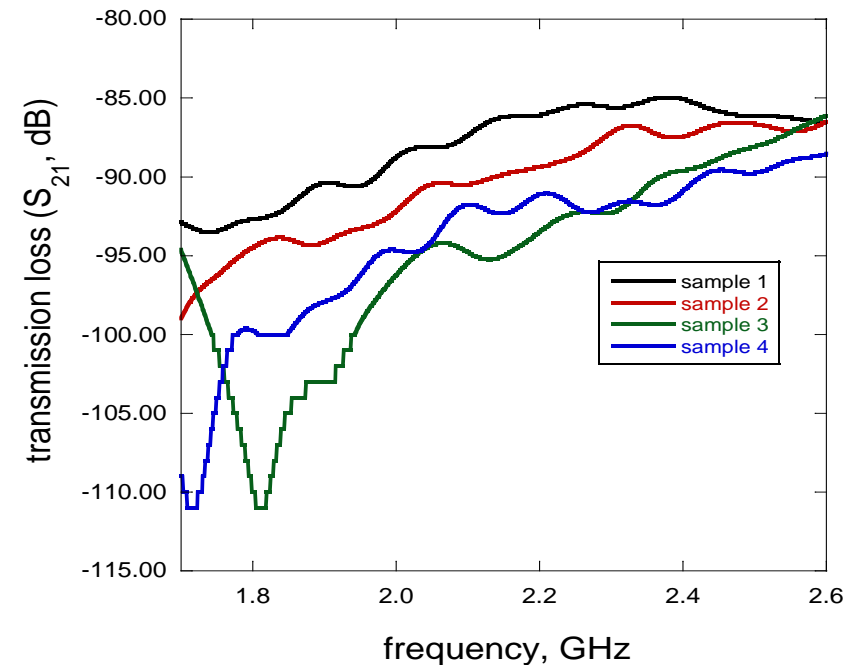
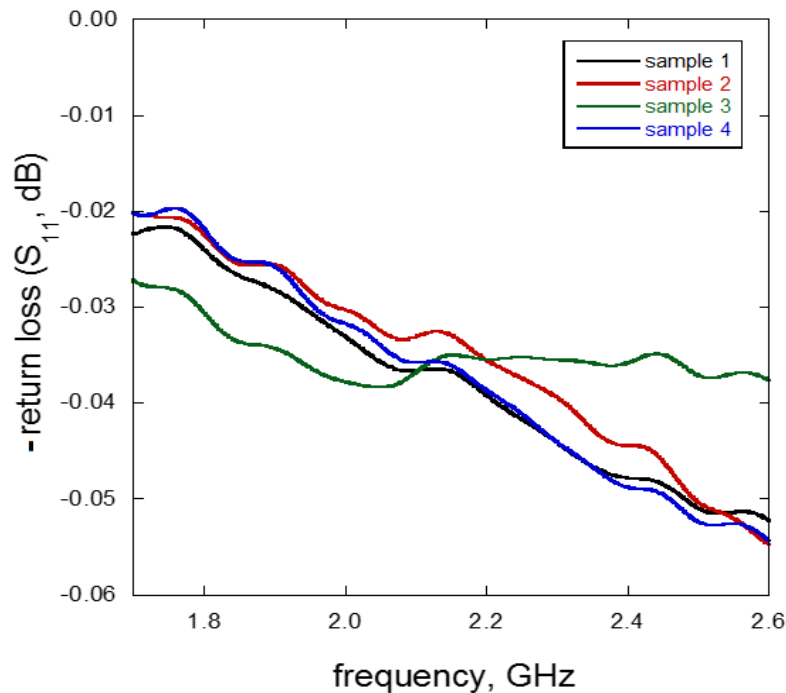
- 8552 IM7 samples inserted in a WR430 waveguide (10.9 x 5.5 cm)
- Reflected and transmitted signals measured using an Agilent E8361A network analyzer
- Signal propagates in the TE₁₀ mode: Electric field is parallel to the sample



Waveguide measurements



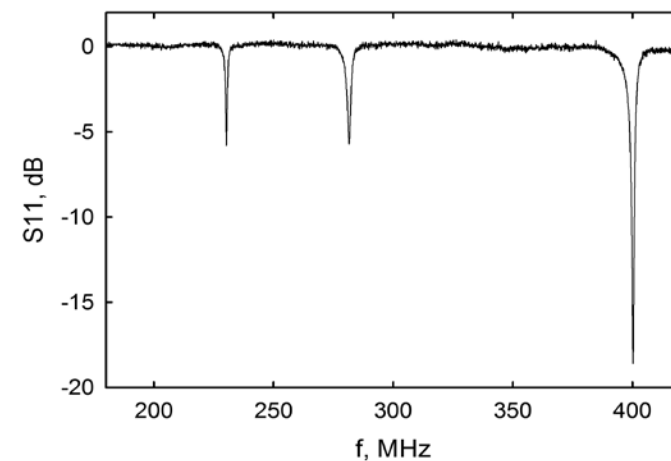
- Return loss is near 0 dB, which indicates a good conductor
- Transmission loss is high but measureable
- Data suggests a composite tank would have good RF modes



Composite cube test



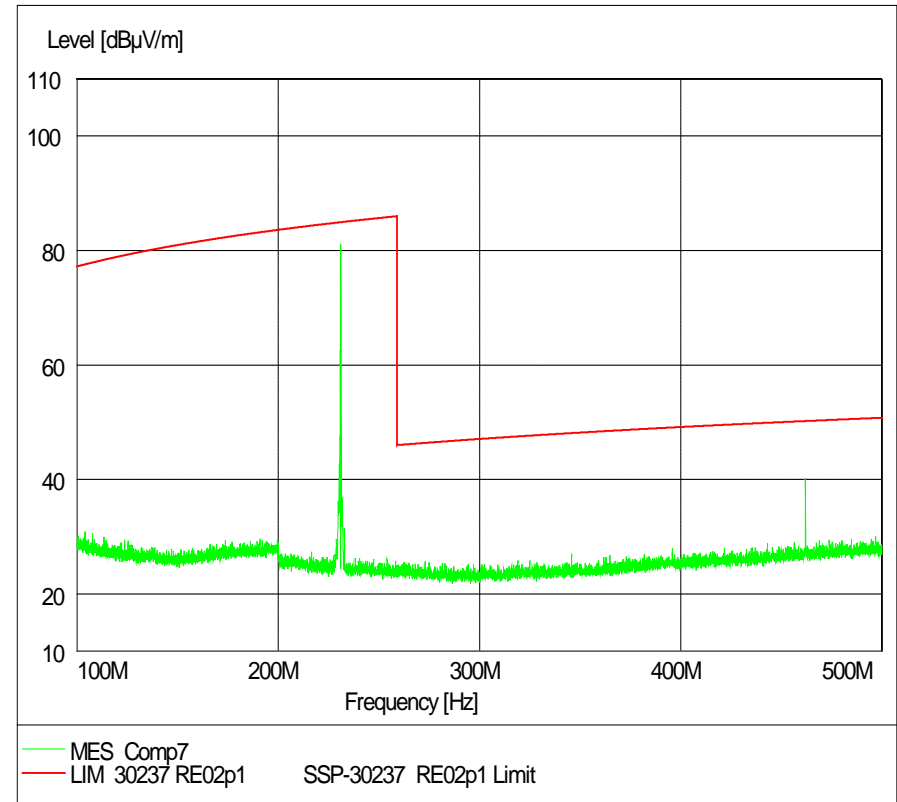
- Constructed a 1m³ box from 8552 IM7 graphite-epoxy panels
- Demonstrated that the composite box supported RF modes
- Measured quality factor in the range $100 < Q < 200$
- Used the box to conduct EMI radiated electric field test



Radiated electric field test from composite cube



- Radiated electric field measured using EMI lab antenna
- 1 mW RF signal was used to excite a single mode at 230 MHz during this test
- Some RF leakage is expected based on the electrical penetration length
- Similar measurement using aluminum box showed 20 dB lower field levels
- Lower radiated field levels could be achieved with a smaller RF signal. Aluminized MLI would also reduce emissions.



— Measured radiated field
— ISS limit line (SSP 30237 Rev F)

Boeing 2.4m composite tank



- 2.4 m diameter graphite fiber composite tank built by Boeing
- Liquid hydrogen testing conducted at NASA MSFC
- Precursor to a 5.5m composite tank

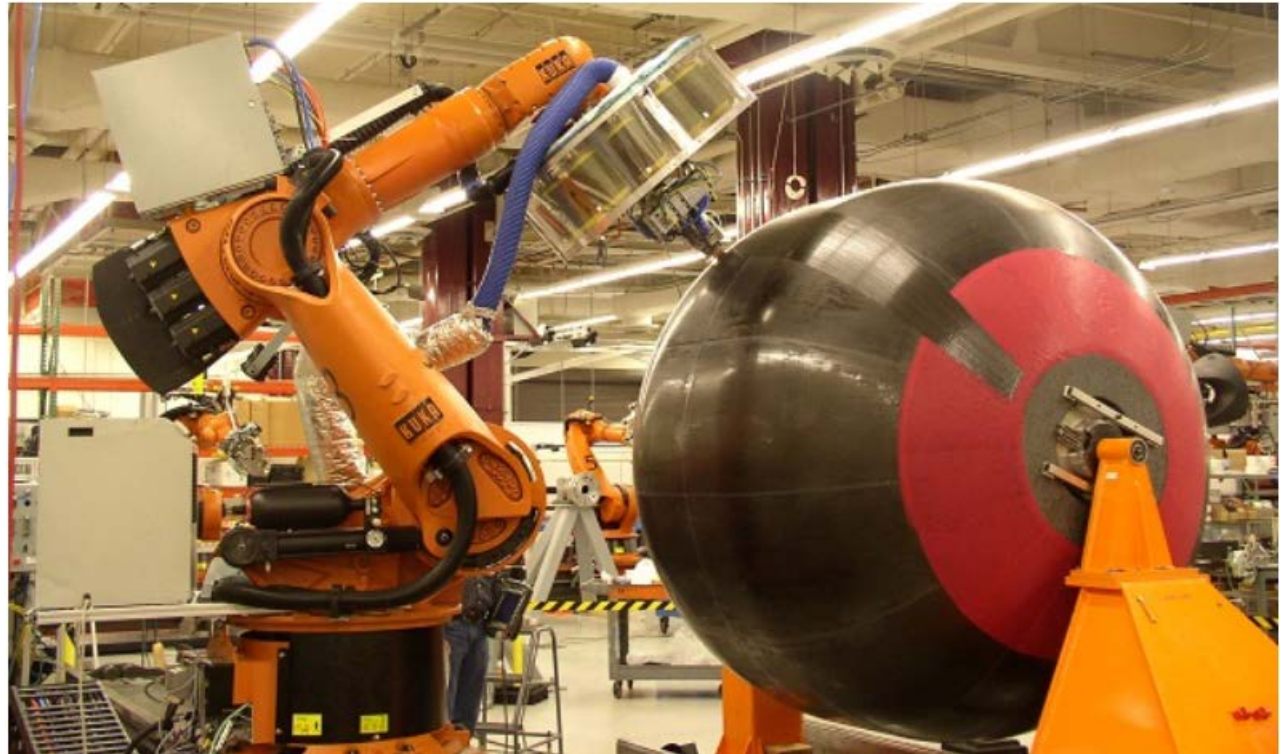
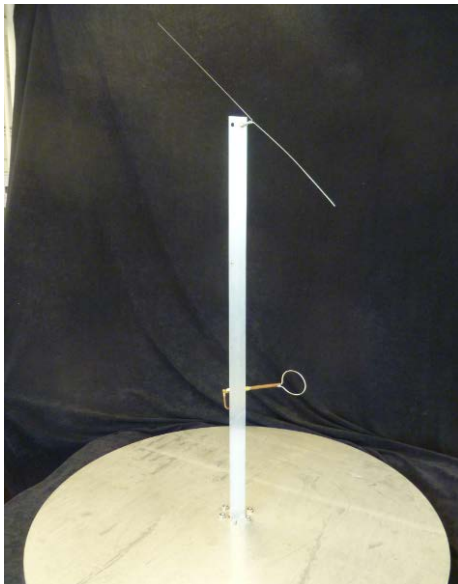


Image credit: Boeing

RF modal testing of the 2.4m composite tank



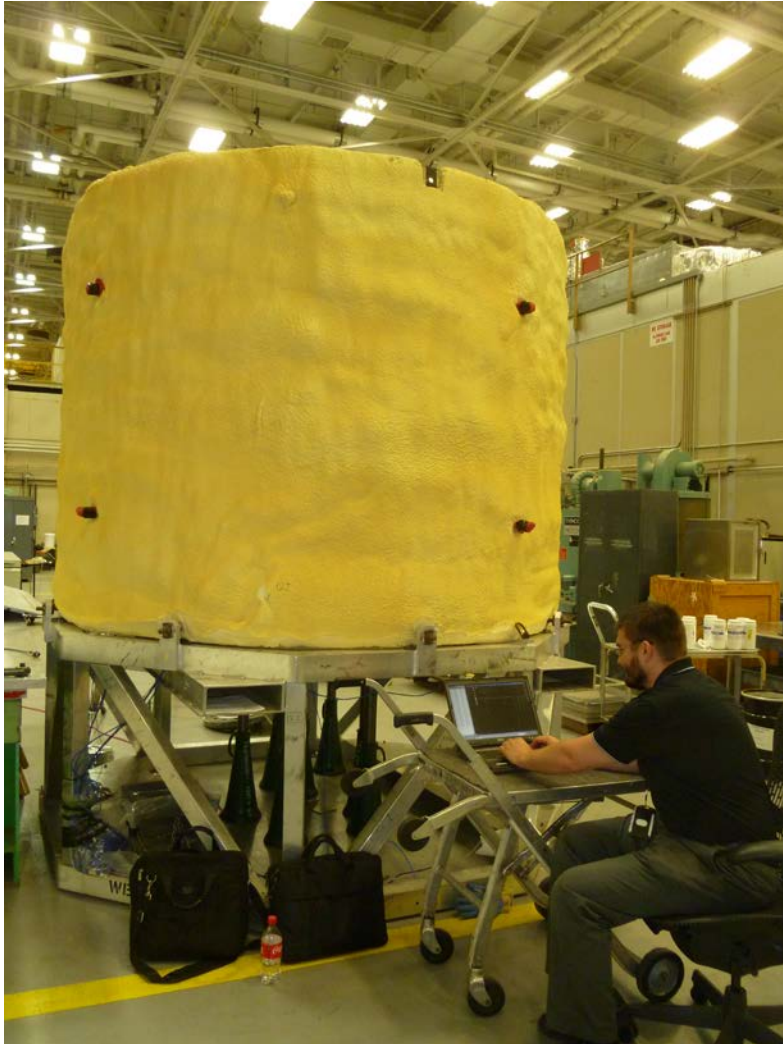
- Aluminum lid and T-bar structure fabricated to conduct RF modal test
- 30 cm dipole and 5 cm diameter loop antenna was used to measure the RF modes
- Several floor jacks used to press-fit the lid to the bottom port



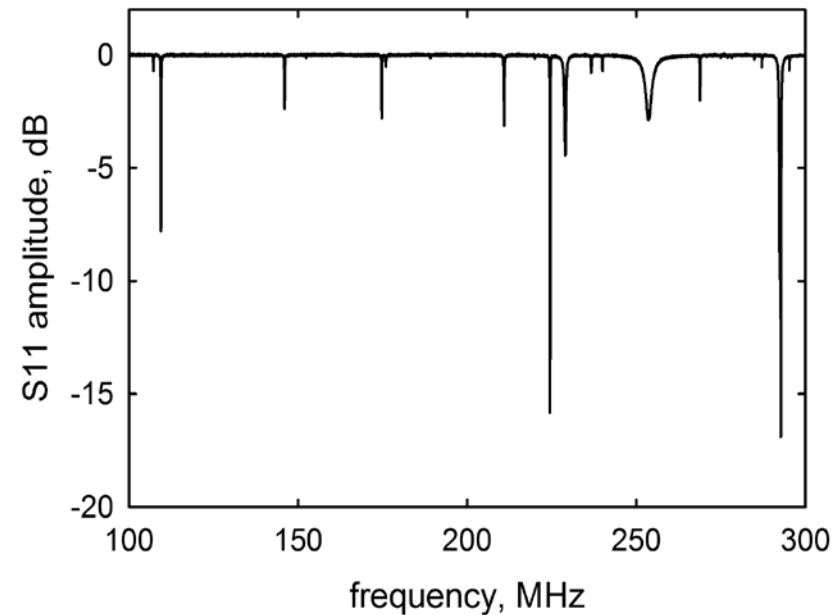
Antenna mount assembly



RF modal testing of the 2.4m composite tank



- RF modal test conducted after cryogenic testing
- Excellent RF modal spectrum observed
- Measured $440 < Q < 2,800$



RF modal testing of the 2.4m composite tank



Converting measured Q to resistivity:

$$Q = \frac{\mu}{\mu_c} \left(\frac{V}{S\delta} \right) \times (\text{Geometrical factor}) = 1,500 \quad \delta = \sqrt{\frac{2}{\mu_c \omega \sigma}}$$

Yields $\rho = 0.06$ ohm-cm

- Somewhat higher than published values for graphite-epoxy composites, but significantly lower than our 4.8 ohm-cm normal-to-plane impedance measurement (as expected)
- Electrical bond between press-fit aluminum lid and tank may lower the Q-factor somewhat
- Larger tanks would have even higher Q's
- Cooling to low temperatures is not expected to have much impact since $\rho(293 \text{ K})/\rho(20 \text{ K}) \sim 1$

- Graphite-epoxy composite tanks are compatible with the Radio Frequency Mass Gauge sensor
- RF mode quality in the 2.4 m composite tank is very good
- Measured $Q \sim 1,500$ in the 2.4m is consistent with expectations based on RF impedance tests of smaller samples
- Very high Q tanks, such as large aluminum tanks, can make RF modal measurements difficult (narrow peaks), so in this respect composites offer an added benefit

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- Special thanks to Justin Jackson at MSFC for helping to enable the RF modal measurements on the Boeing 2.4 m composite tank